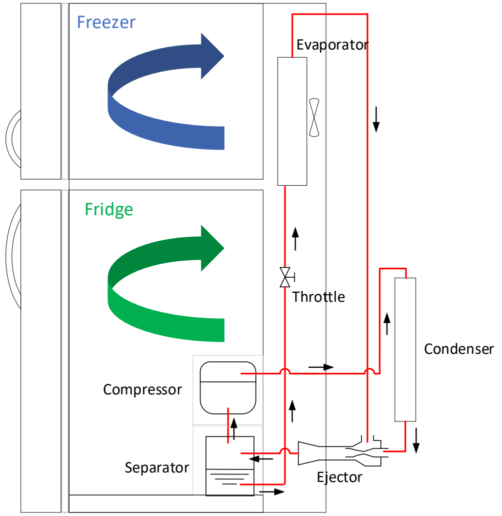
ISO: Next-Generation Domestic Refrigerator with Unprecedented Performance Using Isobutane as Refrigerant



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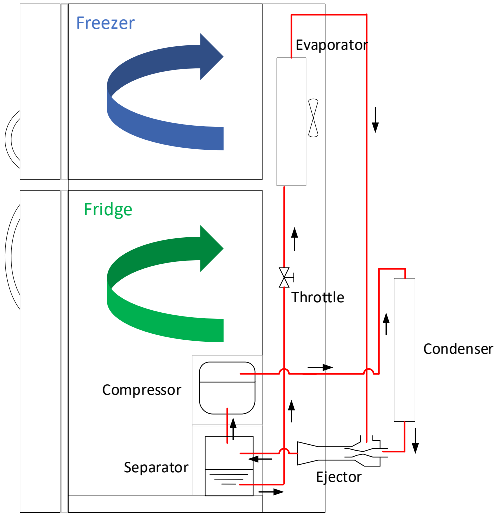
WBS #03.02.06.46.

Project Summary

Objective and outcome

The objective of the project is to design and demonstrate the next generation of energy efficient domestic refrigerators with isobutane (R600a) as the ultra-low GWP refrigerant. This will be accomplished by exploring new and innovative cycle designs and system level improvements to existing vapor compression cycle designs.



OAK RIDGE National Laboratory

Whirlpool CORPORATION

Team and Partners

Kashif N., Cheng-Min Y., Muneeshwaran M., Brian F. (ORNL)

Shean H., Alberto G., Chris H. (Whirlpool)

Stats

Performance Period: Sep 2022 –Sep 2025

DOE budget: $900k, Cost Share: $225k

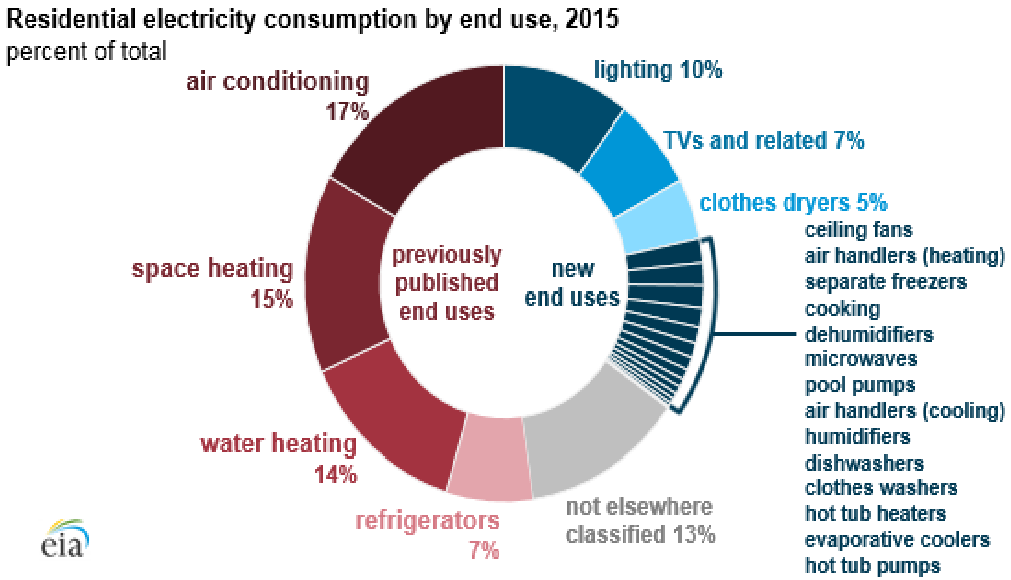
Milestone 1: Completion of thermodynamic analysis

Milestone 2: Development of prototype

Milestone 3: Demonstration of 10% improvement in efficiency using iso-butane as refrigerant

Problem

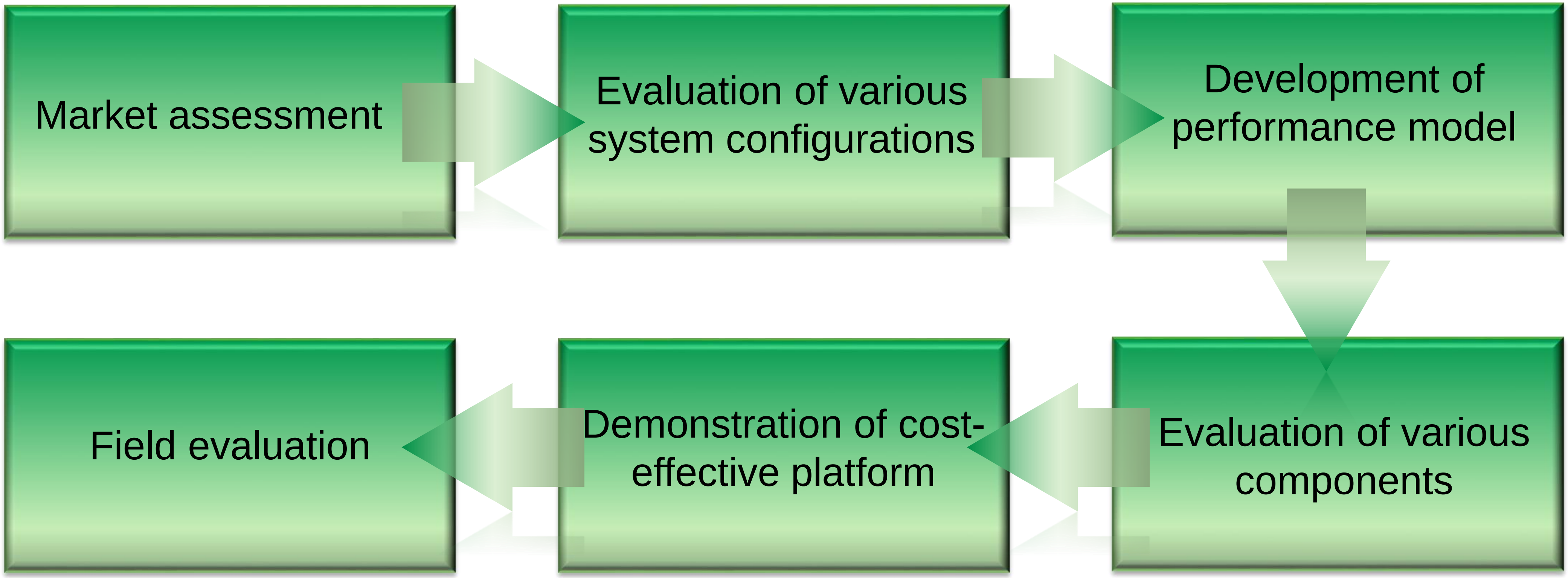
- A domestic refrigerator is an indispensable household appliance for chilled food storage, and many households use more than one.
- According to the 2015 Residential Energy Consumption Survey (RECS), refrigerators in the United States consumed 303 trillion Btu, which accounts for 7% of US residential electricity consumption.
- R134a (GWP100 = 1,300), a hydrofluorocarbon (HFC) refrigerant, is the most common refrigerant for domestic refrigeration applications.



(https://www.eia.gov/todayinenergy/detail.php?id=37813)

R600a is an ideal refrigerant due of its minimal environmental impact, higher energy efficiency

Solution Approach



Design and demonstrate the next generation of energy efficient domestic refrigerators with isobutane (R600a) as the ultra-low GWP refrigerant

Risks and Mitigation Strategy

Risk items	Mitigation strategy
Compatibility of work fluid	To ensure compliance, the project team will conduct a comprehensive compatibility evaluation of various materials with isobutane.
Target charge reduction	UL 60335-2-24 now allows 150 g of hydrocarbons for appliances; therefore, the team will comply with this allowable charge limit.
Compressor technology	Isobutane compressors have been commercialized for relatively smaller cold boxes to store snakes and drinks.
Cost effectiveness	Cost-effectiveness will be achieved via cost model development. Whirlpool will facilitate the process by engaging appropriate in-house expertise.
Market acceptance	The development of an isobutane-based product line is aligned with Whirlpool business plan, so we expect this will be a low-risk item.

Project Impact

Potential energy savings are 100 TBtu with 40 Mton reduction in GHG emissions at minimum

- Opportunities to create more than 4000 new jobs
- Paving the path for US manufacturer to expand to international markets

An improved domestic refrigeration technology with

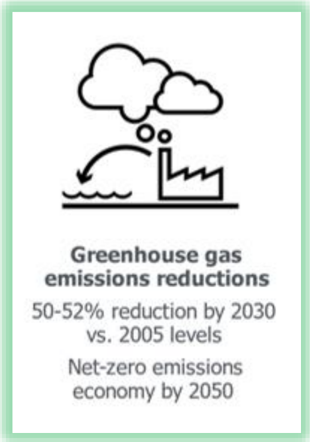
- Unprecedented Coefficient of Performance (COP)
- Reduced manufacturing cost

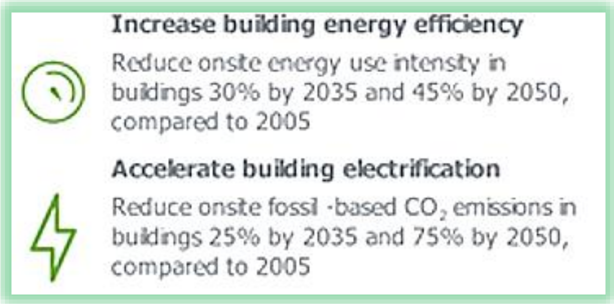
Enabling development for deployment A3 refrigerants

- Reduction in refrigerant charge
- Reduced cost of the working fluid
- Reduced required maintenance due to compact design

Implications for additional processes

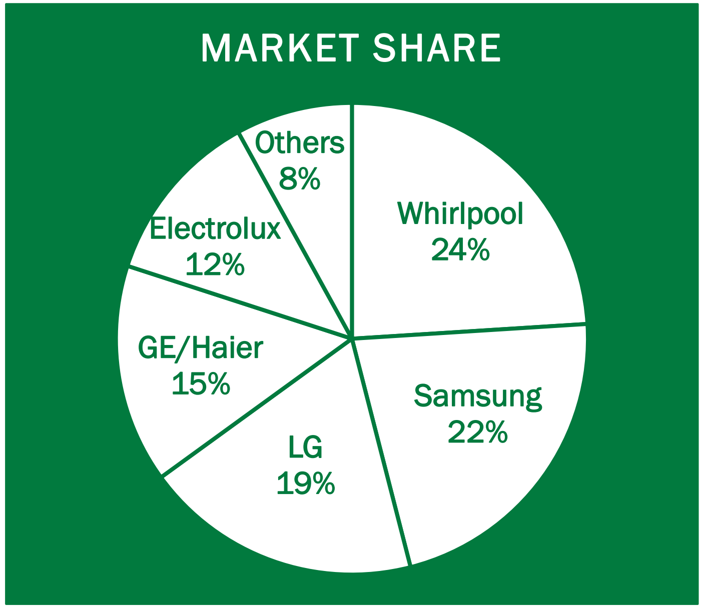
- Residential air cooling/heating, refrigeration, Process water heating



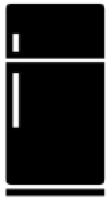


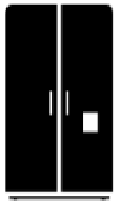
Preliminary Development - Market Assessment

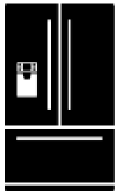
Primary manufacturers & market share



Domestic refrigerator categories



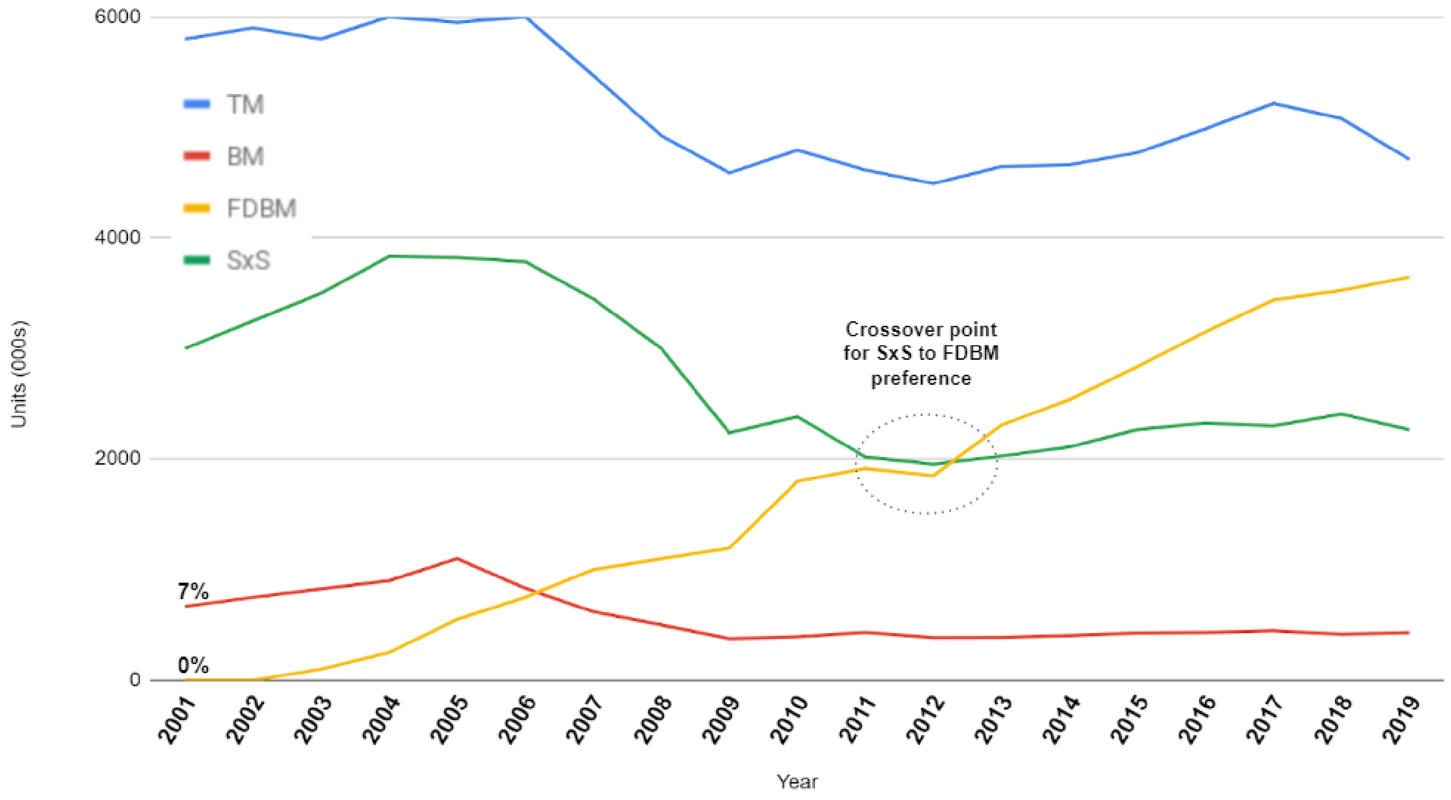




	Top mount	Side-by-Side	French door bottom mount
Average Price (TraQline)	$787	$1,471	$2,120
Industry Size (AHAM)	5.0M units	2.5M units	4.5M units
2022 Growth (est)	-1.9%	-3.7%	-0.9%
Forecast (thru 2027)	-0.2% CAGR	+3.6% CAGR	+0.5% CAGR

Annual unit volume for domestic refrigerators is ~13 million units

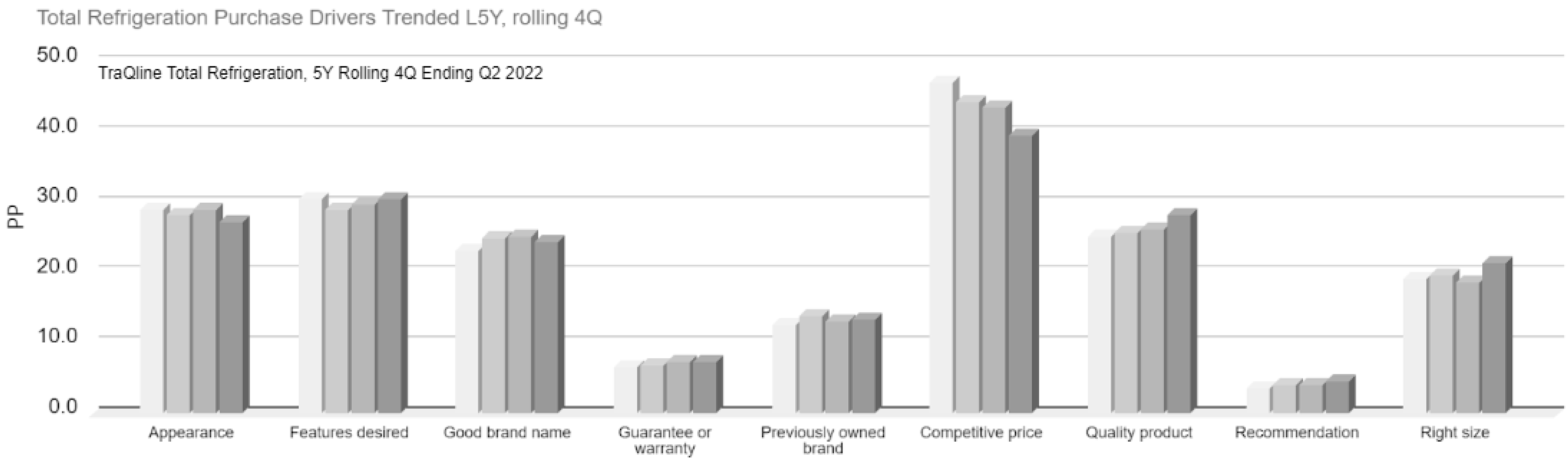
Preliminary Developments - Market Assessment



- TM experienced a negative growth rate of -1.9% for 2022. Additionally, a compound annual growth rate also stands at -0.2% for TM.
- SxS and FDBM also showed a negative growth rate of -3.7% and -0.9%, respectively.
- The expected compound annual growth rate for SxS and FDBM is nearly 3.6% and 0.5%, respectively.

TM – Top mount
BM – Bottom mount
FDBM – French door bottom mount
SxS – Side-by-Side

Preliminary Developments - Market Assessment

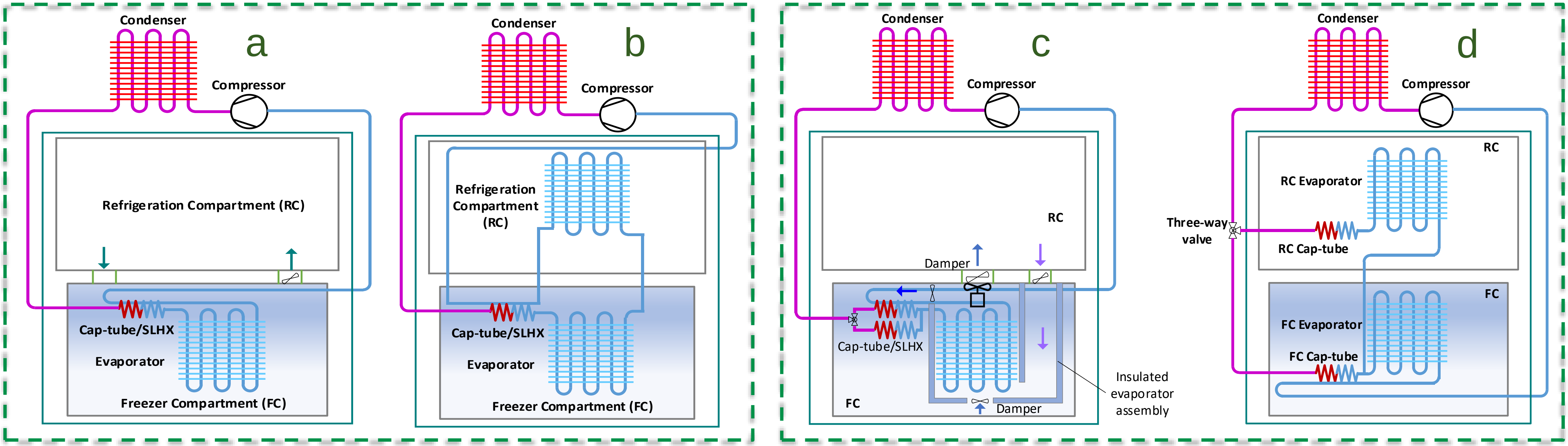


Main driving forces for domestic refrigerator purchase

Price > Features desired > Appearance > Good brand name > Quality > Others

- The importance of price has slightly decreased in L5Y, 4Q, and consequently, it is compensated by a slight increase in quality preference. The reason may be due to the rise in food quality awareness post pandemic

Preliminary Developments – Performance Modeling



(a) Single evaporator & single temperature (b) series dual-evaporator refrigeration system (c) single dual-temperature evaporator d) a sequential series dual-evaporator refrigeration system.

Refrigerant	R134a	R600a
COP	*1.554*	*1.697*
Q_{evap}	*183.5 W*	*326.8 W*

Refrigerant	R134a	R600a
COP_1	*1.554*	*1.697*
COP_2	*2.683*	*3.035*

T_{cond}: 38.5°C; $T_{evap,1}$: -24.8°C; $T_{evap,2}$: -2.2°C; $T_{superheat}$: 24.4°C; $T_{subcool}$ 5.5°C

Preliminary Developments – Test standards

Test conditions	ANSI/AHAM HRF-1 2019	JIS C 9607	ISO15502/IEC62552
Ambient temperature	32.2ºC	15ºC	25±0.5ºC (Subtropical regions)
		30ºC	32±0.5ºC (Tropical regions)
Relative humidity	-	75±5%	45-75%
Fresh food compartment - Temperature	3.9ºC	3ºC	5ºC
Freezer compartment temperature depending on product classification	-9.4ºC	-6ºC	-6ºC
	-17.8ºC	-12ºC	-12ºC
		-18ºC	-18ºC
Door openings	No	Yes, (with a full door opening of at least 5 s)	No
Load in refrigerator	No	Yes	Yes

ANSI – American National Standard Institute
AHAM – Association of Home Appliance Manufacturers
JIS – Japanese Industrial Standards
ISO – International Organization for Standardization

Work Plan for Prototype Development

Phase I: Baseline tests

- Standard instrumentation following AHAM standard
- Two ambient conditions: 70 F and 90F
- Measure E_{AHAM}, E_{90F}, and E_{70F}.
- Compare with Whirlpool's data

Phase II : Instrumentation

- Standard instrumentation per AHAM standard
- Additional sensors: temp. and flow rate
- One ambient conditions: 90F
- Measure E_{90F} (E_1 only)

Phase III : Concept analysis

- Open system
- Test proposed concepts and configurations
- One ambient conditions: 90F
- Measure E_{90F} (E_1 only)
- E_2 is measured if change defrost design

Phase IV : Final validation

- Winning concepts
- Standard instrumentation following AHAM standard
- Two ambient conditions: 70 F and 90F
- Measure E_{AHAM}, E_{90F}, and E_{70F}.
- 24 hour tests

Preparison of refrigerator baseline tests

Refrigerators for baseline tests

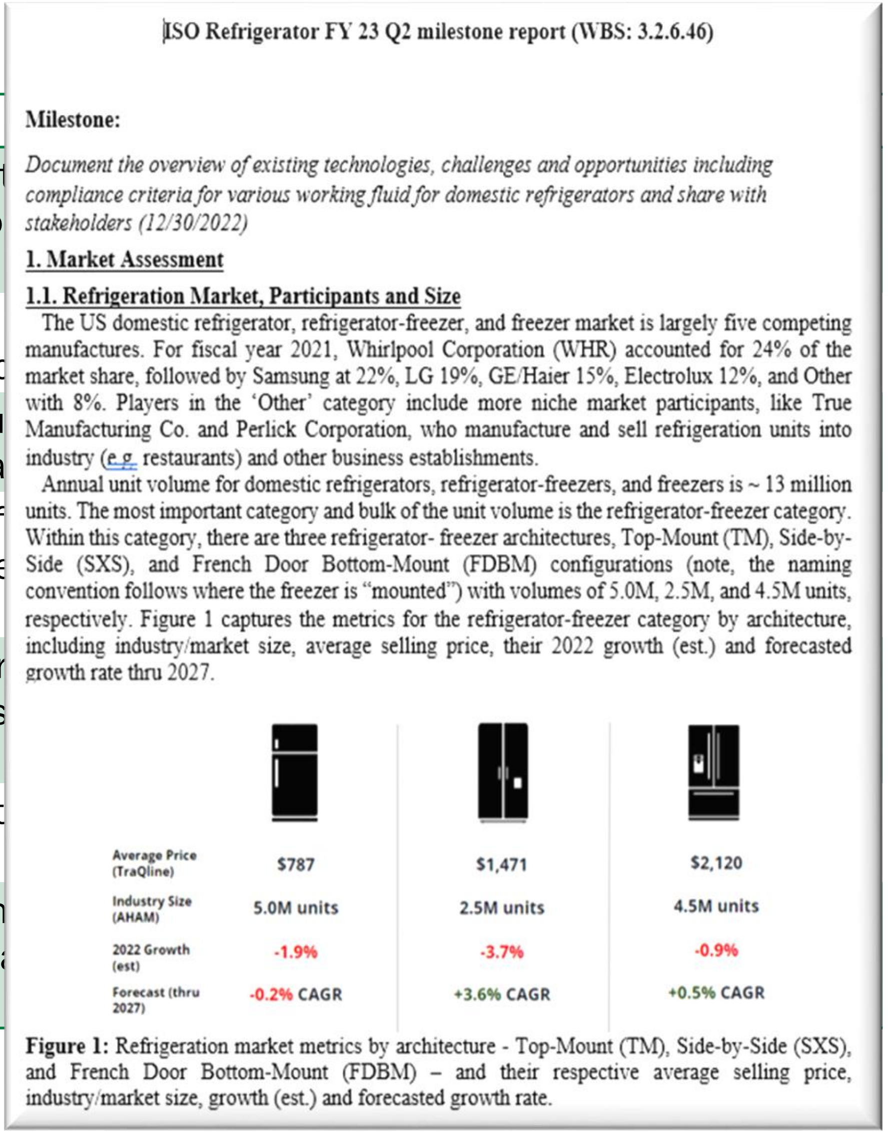
Data acquisition cart

Weighted temperature sensor

Watt transducer

Future work

Milestone Name/Description	Criteria
Drop-in-replacement analysis	Complete the lab scale evaluation of a drop-in-replacement working fluid is replaced with isobutane and conduct perfo environment
Design and fabrication of components-Compressor selection	Complete the detailed investigation of various compressor capacities is completed and select at least one feasible tec
Design and fabrication of components-Heat exchanger sizing	Complete the analysis of various heat exchanger design cu for evaporator and condenser to meet the required heat ca
Analysis of defrost technologies	Establish a comprehensive overview of various existing def heaters and other active measures (hot gas bypass) and se energy efficient framework for deployment
System integration and shakedown testing-alpha prototype	Complete the development of a prototype incorporating var exchanger etc.) and conduct the shake down testing to ens and ready for lab scale performance evaluation
Field evaluation- beta prototype	Complete at least one deployment in the field and initiate t realistic operating conditions with the support of industrial
Final report and development of deployment strategy	Final report on the prototype development, materials and n efficiency demonstration. Include a roadmap on the applica all domestic refrigeration systems.



ISO Refrigerator FY 23 Q2 milestone report (WBS: 3.2.6.46)

Milestone:

Document the overview of existing technologies, challenges and opportunities including compliance criteria for various working fluid for domestic refrigerators and share with stakeholders (12/30/2022)

1. Market Assessment

1.1. Refrigeration Market, Participants and Size

The US domestic refrigerator, refrigerator-freezer, and freezer market is largely five competing manufactures. For fiscal year 2021, Whirlpool Corporation (WHR) accounted for 24% of the market share, followed by Samsung at 22%, LG 19%, GE/Haier 15%, Electrolux 12%, and Other with 8%. Players in the 'Other' category include more niche market participants, like True Manufacturing Co. and Perlick Corporation, who manufacture and sell refrigeration units into industry (e.g. restaurants) and other business establishments.

Annual unit volume for domestic refrigerators, refrigerator-freezers, and freezers is ~ 13 million units. The most important category and bulk of the unit volume is the refrigerator-freezer category. Within this category, there are three refrigerator- freezer architectures, Top-Mount (TM), Side-by-Side (SXS), and French Door Bottom-Mount (FDBM) configurations (note, the naming convention follows where the freezer is "mounted") with volumes of 5.0M, 2.5M, and 4.5M units, respectively. Figure 1 captures the metrics for the refrigerator-freezer category by architecture, including industry/market size, average selling price, their 2022 growth (est.) and forecasted growth rate thru 2027.

Average Price (TraQline)	$787	$1,471	$2,120
Industry Size (AHAM)	5.0M units	2.5M units	4.5M units
2022 Growth (est)	-1.9%	-3.7%	-0.9%
Forecast (thru 2027)	-0.2% CAGR	+3.6% CAGR	+0.5% CAGR

Figure 1: Refrigeration market metrics by architecture - Top-Mount (TM), Side-by-Side (SXS), and French Door Bottom-Mount (FDBM) – and their respective average selling price, industry/market size, growth (est.) and forecasted growth rate.

Thank you

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Kashif Nawaz, Section Head of Building Technologies Research; Group Leader of Multifunctional Equipment

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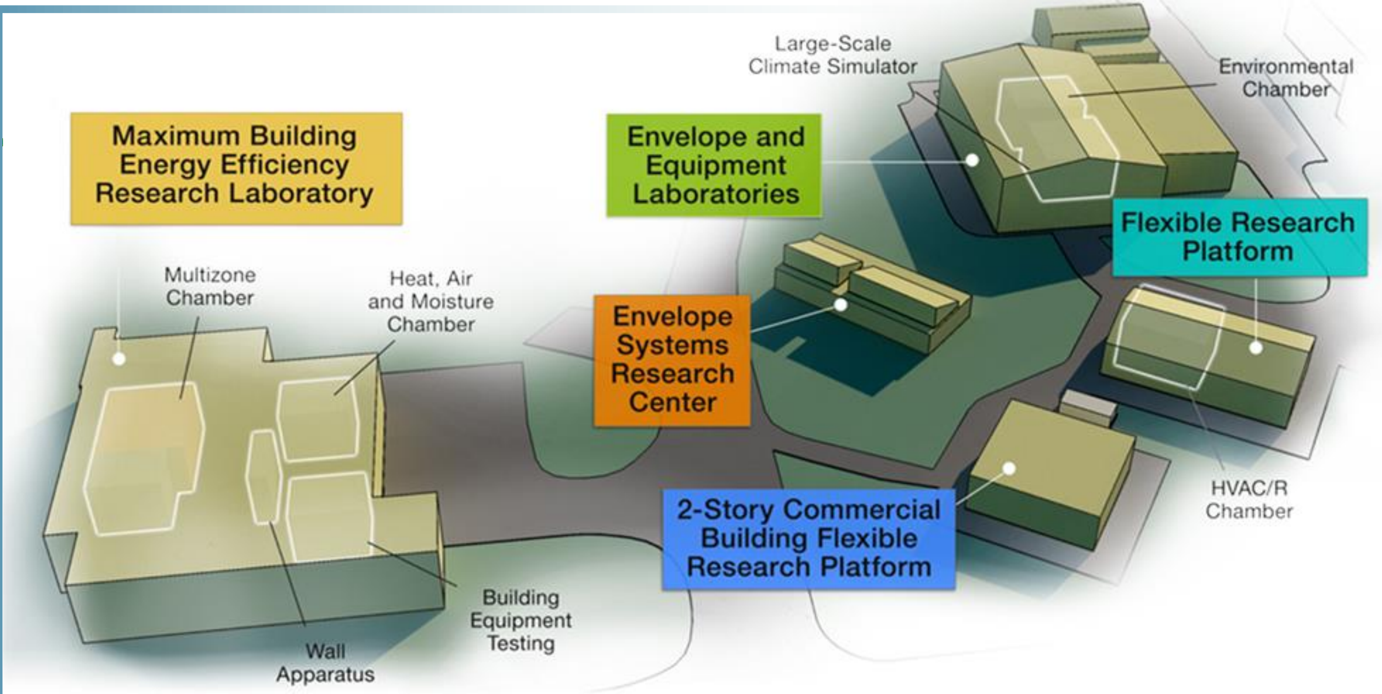

ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 60,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results

236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Execution

	FY2023				FY2024				FY2025			
Planned budget	$300,000				$300,000				$300,000			
Spent budget												
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Market analysis												
Performance modeling (basic configurations)												
Drop in replacement analysis												
Performance modeling (advanced configurations)												
Alpha prototype development												
Alpha prototype evaluation												
Beta prototype development												
Beta prototype evaluation												

Project Team

Kashif Nawaz
Project management
Protype development

Cheng-Min Yang
Thermodynamic analysis
Instrumentation

Muneesh Murugan
Experimentation
Data analysis

Alberto Gomes
Experimentation
Data analysis

Chris Hartnett
Instrumentation
Data analysis

Brian Fricke
Experimentation
Performance modeling

Shean Huff
Instrumentation
DAQ development